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Precision Nonlinear Low Current Meter

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Abstract. Mobile measuring systems that allow small electric parameters to be estimated with high accuracy in real time are relevant for leading edge high-tech applications. In most cases, measurements are carried out with the use of piecewise linear scales and corresponding linear analog-to-digital converters. This technology does not meet the requirements of high measurement accuracy due to errors in the automatic switching of the measuring scale when an input signal varies in a wide range, for example, 100 dB. A new method for measuring small electric parameters based on a nonlinear scale is proposed. The nonlinear analog-to-digital meter having been developed and tested is described. An exponential function with an index $m < 1$ is used as a scale. The results of measuring nanoampere currents ranging between 1 nA and 1 μA, obtained with the help of the meter model, are presented.

INTRODUCTION

Real-time precision measurements of low electrical currents serve as a basis for promising embedded data processing systems. Electronics of micromechanical accelerometers [1], [2], technological systems for monitoring the parameters of microelectronic devices in the process of their manufacture and operation [3], mobile recorders of physical and chemical processes with very low energy values [4] can be considered as examples of such systems. Strict requirements for measurement systems are imposed by mobile data processing and control systems, for example, systems for checking the insulation resistance between signal contacts of transport cable connectors. For tomorrow's mobile systems, the following mutually contradictory requirements should be taken into consideration:

- dynamic range of input signals change is not less than 100 dB;
- input signals for currents range from 10^{-9} to 10^{-10} A;
- the total relative measurement error is about 0.01%;
- the number of measurement channels is up to 256, the measurement time is about 10^{-3}s for all channels;
- the weight of a 16-channel measuring complex must not be more than 150 g;
- the power consumption of the whole measuring complex must not exceed 5 W.

Precise measuring systems are characterized by maximum sensitivity to minimal values of input signals and by low sensitivity under increasing signals. It is connected with the following goals:

- ensuring maximum reliability while measuring small parameters;
- optimization of hardware costs of analog-to-digital converters (ADC).

For example, to measure currents of ionization sensors in X-ray computer tomography, it is necessary to ensure the order of the total relative measurement error not more than $\left(\alpha / \sqrt{I} \right)$ [%], where I [nA] is an output current of a sensor, α is the coefficient of attenuation of radiation in biological tissue. For $\alpha = 1$: for $I = 1$ nA, $\delta = 1$ %; for $I = 1000$ nA, $\delta = 0.03$ %. Taking into account the required measurement error, the minimum necessary number of ADC digits is 16. If we take into account that the attenuation coefficient of radiation in biological tissue α can have an order of 10^{-2}, the number of digits for the ADC is not less than 24. Thus, the direct conversion of input signals into a digital code can be a scientific and technical problem. Therefore, the measuring scale of modern meters is a set of

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piecewise linear intervals, in each of which a linear transformation with a predetermined coefficient is used. Switching from one interval to another while measuring signals rapidly changing in time may result in a sharp short-term change in amplitude, which increases the measurement error. This article is devoted to the development of a meter which is largely free from these disadvantages.

MEASURING SCALE

To take into account the requirements (especially concerned measurement accuracy) and characteristics mentioned above, it is advisable to avoid linear transformation in the form "X → kX → N", where X is a measured signal, N is a digital code, k = const is a scale factor. Instead of it, a two-step functional conversion of input signals in the form "X → O(X) → N", where O is nonlinear transformation, for example an analytical function, can be used as a basis for tomorrow's technology for precise measurement of small currents in real time. In this case, the following nonlinear scale is relevant:

$$\left(\frac{\partial F}{\partial X}\rangle kX, \forall X \leq X^{*}\right) \vee \left(\frac{\partial F}{\partial X}\langle kX, \forall X\rangle X^{*}\right), \tag{1}$$

where X^* is the boundary dividing the measurement interval of an input signal into two sub-intervals. It results from (1) that the transformation $O(X)$ may be an analytic function $F(X)$, such as a logarithmic or power function with an exponent less than 1. Under $X \leq X^*$, the sensitivity of a meter with the nonlinear scale in the form (1) is higher than the sensitivity provided by the linear scale; under $X > X^*$, the sensitivity of a meter with the linear scale is higher.

The realization of the measuring scale in the form (1) leads to functional microelectronics, in which electronic circuits reproducing required functional dependencies are used. At the current and future stages of microelectronics development, this trend restores the concepts of analog and analog-to-digital functional converters successfully developed and produced by Soviet researches and engineers in the 1950s and 1960s. The developers of modern real-time systems are increasingly coming up with such ideas if either high accuracy or wide range of measured parameters can no longer be achieved using purely digital approaches. Currently, some attempts are being made to implement tasks using analog processors. The DARPA agency has begun funding the development of an experimental model of a surveillance and intelligence system based on optical sensors [5]. In this project, the use of analog solver modules for the implementation of algorithms that have recently been considered purely "digital" is being worked out.

The results of the development of an electrical circuit implementing functional transformation in a multichannel precision data acquisition system (DAS) for real-time systems are described in the article.

METER OPERATION

Theoretical studies of possible principles for the construction and operation of a precision low-current meter were carried out using simulation of circuit solutions based on the SPICE system and Verilog language tools. The results of research and prototyping of key circuit solutions have shown that it is advisable to carry out precision measurements of small electrical parameters using ADC with two-cycle (push-pull) integration [6].

The push-pull integration method is based on charging a capacitor in the feedback of an operational amplifier (OA) with the help of the measured input current during the first conversion cycle. OA input cascades have a resistance of more than 10^9 Ω, which limits the OA input current to picoampere values, so that the charge of the capacitor occurs almost without loss.

Further, in the second conversion cycle, the capacitor is discharged to some predetermined voltage value on its plates. The change in OA output voltage at this stage of conversion is determined by the discharge of an integrating capacitor.

Push-pull integration can potentially provide the maximum conversion accuracy since the same capacitor is involved in both charge and discharge processes. This eliminates the influence of variations in the technological parameters of the capacitor on a systematic integration error. Moreover, the additive mixture of input current and noise is simultaneously averaged.

In the push-pull ADC, linear measuring scales are most often used. In this case, to provide a large dynamic measuring range (100 dB), it is necessary to increase the power supply voltage, this being undesirable for equipment with autonomous power supply. A dynamic range of a measured signal is generally increased by applying a nonlinear scale with piecewise linear approximation [6]. A well-known disadvantage of piecewise linear approximation, as was mentioned above, is a significant measurement error during switching interval scales. This is caused by the so-called "dead" zone in the comparator, due to which the total measurement error is increased. A smooth non-linear scale of a special type, which is implemented in the described meter, is fundamentally free from this disadvantage. To obtain a nonlinear measuring scale, a specially designed controlled current source is used to discharge an integrating capacitor. The type of nonlinearity is determined by a discharge current of the integrating capacitor in time.

Operation of the developed meter is based on a nonlinear AD conversion of input currents into digital codes. A nonlinear scale of the form $N = k(I_{in})^m$ is dynamically formed in each measurement channel as a functional conversion scale, where k is the scale factor, I is the input current, $m = 0.5$. It was shown in [7] that the proposed scale provides a smaller total relative measurement error over the entire range of input currents, compared with the linear version $m = 1$, which is widely used at present.

Another specific feature of the low current meter under study is the compensation of external noise influence on the circuit operation. In particular, it is electromagnetic radiation that affects mainly input circuits of small electrical signal meters as an additive noise. To reduce the influence of the electromagnetic background on the meter operation, a compensation method was applied in addition to the push-pull integration. It works as follows. A mix of signal and noise (the input signal of the meter) is supplied to the inverting OA input; only the external noise is supplied to the non-inverting OA input. These signals are subtracted one from the other in the OA, which allows common-mode interference rejection.

The flow chart of an integrating ADC with a non-linear scale and compensation of the influence of electromagnetic background is shown in Fig. 1.

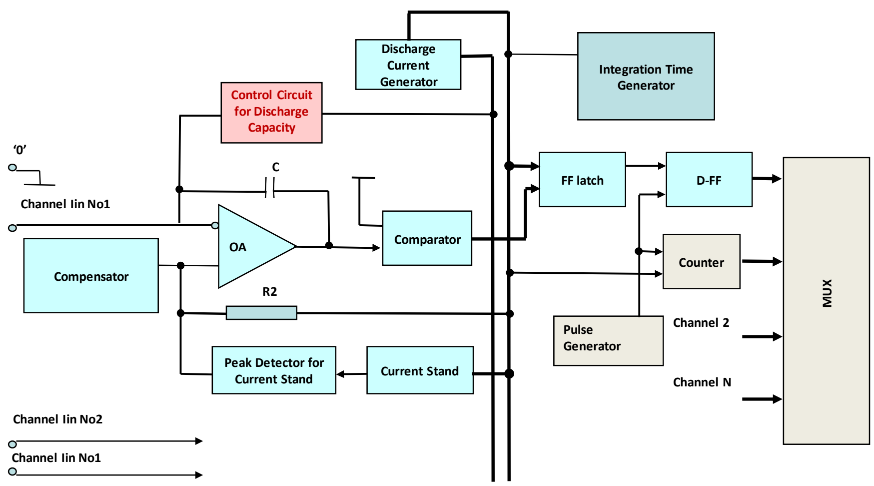

FIGURE 1. Flow chart of the small current meter on the basis of nonlinear ADC [8]

The meter consists of analog and digital parts. The analog part contains a measuring cell and a sawtooth generator providing a non-linear discharge of the integrating capacitor. The output of the measuring cell is a short pulse, the time position of which is determined by the discharge of the capacitor in the second cycle of the conversion. The sawtooth generator provides the power dependence of the above-mentioned type with $m = 0.5$. The time chart of the meter operation is shown in Fig. 2

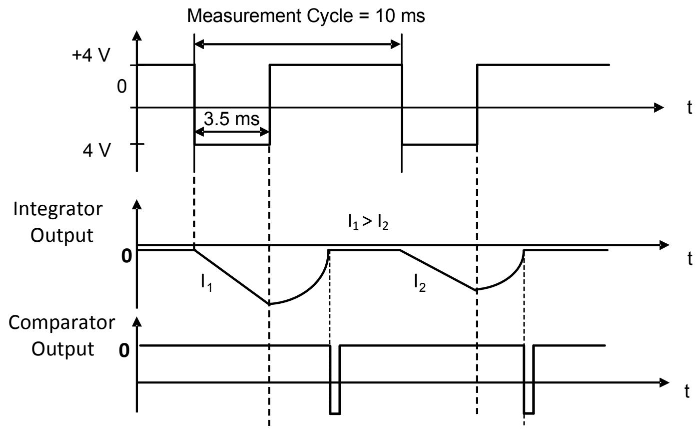

FIGURE 2. Time chart of the small current meter based on nonlinear ADC

The digital part provides

- generation of all control signals organizing the push-pull mode of the measuring cell operation;
- high-frequency pulse generation;
- counting a number of pulses of a high-frequency generator from the beginning of the second conversion cycle till the moment of the appearance of a short pulse at the output of the measuring cell.

The number of pulses, i.e. the contents of the counter, is the result of converting the input analog signal to a digital code. The digital part is based on the standard STM32L-Discovery board.

EXPERIMENTAL STUDY OF THE METER

At the final stage of the work, a 4-channel prototype of a low current meter was developed and tested under normal conditions. The SourceMeter Keithley 2450 calibrator was used as a reference current source of the nanoampere range. The output digital codes of the calibrator were recorded to the computer's memory and graphically displayed on the monitor.

The results of measuring currents in the range from 0 to 900 nA for one of the channels are given in Table 1.

TABLE 1. Output parameters for one channel of the meter at different values of the input current

I_{in}, nA	M, units	$\Delta = (M - \overline{M})_{max}$	$\delta = (\Delta/M)$, %	T, s
0	733	6	0.82	35
1	865	5	0.58	12
2	982	4	0.41	20
4	1183	3	0.25	22
8	1513	4	0.26	21
16	2022	4	0.20	21
32	2788	2	0,07	21
64	3902	2	0.05	21
128	5505	1	0.018	21
256	7800	2	0.026	13
512	11062	1	0.009	20
900	14708	2	0.013	20

The main results of the experiments with the meter prototype are as follows:

- The non-linear measuring scale provides a stable measurement of currents in the range of 60 dB without switching.
- The total relative deviation of the output codes does not exceed 1% for an input current of 1 nA and 0.03% for 1000 nA.
- A high sensitivity of the meter operation has been achieved, i.e. the meter provides non-zero code values for input currents of 50 pA.

- Stable operation of the meter prototype has been ensured for 4 hours of operation.

CONCLUSION

The basic principles and operation of a precision wide-range measuring instrument of low currents in real time has been studied. The result of the research is a patented method based on a non-linear ADC for measuring current. The developed meter with a non-linear scale provides a smaller total relative error of current measurement than a meter with a linear scale over the entire range of input currents (60 dB). The prototype of the nonlinear low current meter has been designed and tested. The tests have proved that the developed nonlinear current meter ensures a minimum relative deviation of output codes. For example, for 1 nA, this deviation does not exceed 0.6%. The high sensitivity and small relative dispersion of output digital codes are appropriate to develop a VLSI multi-channel meter for applications to mobile measuring complexes.

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